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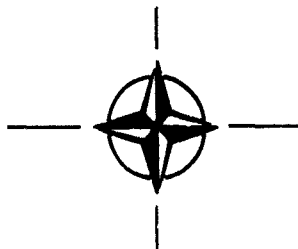
**THE DETERMINATION OF THE FLUTTER SPEED
OF A T-TAIL UNIT BY CALCULATIONS,
MODEL TESTS AND FLIGHT FLUTTER TESTS**

by

J. C. A. BALDOCK

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REPORT 221

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THE DETERMINATION OF THE FLUTTER SPEED
OF A T-TAIL UNIT BY CALCULATIONS, MODEL
TESTS AND FLIGHT FLUTTER TESTS

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J.C.A. Baldock

This Report was presented at the Fourteenth Meeting of the Wind Tunnel and Model Testing Panel, held from 20th to 21st October, 1958, in Copenhagen, Denmark

SUMMARY

The comprehensive investigation made to determine the fin flutter speed of the Handley Page Victor is briefly described. This investigation included low speed wind tunnel flutter model tests, calculations and flight flutter tests on the full scale aircraft. The comparison of estimates for fin flutter speed and the results of the flight tests showed that good agreement was obtained for the fin flutter speed, in spite of differences in the ground resonance modes and in the sub-critical response. General observations are made with regard to the value of low speed wind tunnel flutter models and the safety aspect of flight flutter tests..

SOMMAIRE

La communication présente un exposé sommaire de l'étude approfondie effectuée pour déterminer la vitesse de flutter de plan de dérive de l'avion Victor de Handley Page. Il s'agit dans cette étude d'essais en soufflerie à basse vitesse réalisés sur une maquette de flutter, de calculs théoriques et d'essais de flutter en vol sur avion en vraie grandeur. Une confrontation des calculs relatifs à la vitesse de flottement de la dérive et des résultats obtenus à la suite d'essais en vol montre une bonne concordance, malgré les différences des modes de résonance au sol et de la réponse sous-critique. Des observations de nature générale sont présentées sur l'importance relative des maquettes de flutter pour essais en soufflerie à basse vitesse et sur la question des essais en vol de flutter, considérés du point de vue de la sécurité.

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NOTATION

C_{LT}	tailplane lift coefficient
M	Mach number
T, θ	see Figure 4
A/C	aircraft

THE DETERMINATION OF THE FLUTTER SPEED OF A T-TAIL UNIT BY CALCULATIONS, MODEL TESTS AND FLIGHT FLUTTER TESTS

J.C.A. Baldock*

1. INTRODUCTION

The purpose of this paper is to describe briefly some aspects of the flutter investigation carried out on the tail unit of the Handley Page 'Victor'. Low speed wind tunnel flutter model tests, calculations, and aircraft tests on the ground (ground resonance tests and stiffness tests) and flight flutter tests were included in the investigation and it is believed that the comparison of the results presented in this paper will prove of general interest.

2. BRIEF HISTORY OF EARLY WORK

2.1 Introduction

The ultimate form of the calculations and the flutter model tests and the need for flight flutter tests depended on developments in the earlier work, which is therefore briefly described.

2.2 Design Stage

The tail unit of the Victor evolved into the prototype form in 1949 (see Figure 1). At that time, before analogue or digital computers were available to us, anything like a comprehensive flutter calculation was out of the question. The philosophy adopted for the flutter clearance of the tail unit was to build a low speed wind tunnel flutter model, to check the structural representation of the model against stiffness tests on the aircraft components as they became available, and finally to check the model results, and also extend the investigation to include Mach number effects, with flutter calculations based on modes measured in ground resonance tests of the completed aircraft.

The emphasis was on main surface flutter, since the control surfaces were to be power-controlled and operated by irreversible screw jacks mounted close to the surfaces. The intention was to eliminate the need for conventional massbalance by ensuring adequate stiffness of the connection between the jacks and the surfaces. This was, in fact, successfully achieved with the rudder and the ailerons. Some difficulty was experienced with the elevators, which are almost equivalent to an all-moving tailplane. This is referred to in Section 2.3.

2.3 Initial Flutter Model Results

The flutter model was finished in 1952 and the first tests showed that the flutter speed of the elevators was critically dependent on the stiffness of its operating circuit. Tests on the aircraft structure before flight showed a lower value for this stiffness than had been estimated. The availability of the flutter model enabled a

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massbalance scheme to be evolved which went part of the way to restore the position. This was not massbalance, in the conventional control surface sense, but empirically positioned masses to increase the critical speed of the basic flexure-torsion flutter of the elevator. There was a limit to the amount of massbalance that could be added before another type of elevator flutter involving overtone bending was brought in. This meant that the first Prototype first flew in December 1952 with a speed restriction. High Mach number flight at high altitude (the main function of the aircraft) was possible, but the maximum speed at low altitude was restricted.

Wind tunnel tests on a flutter model of the complete aircraft indicated that the wing had the bare minimum margin on design diving speed, and further tests on the tail unit flutter model were interpreted as showing that the fin could be cleared to the design diving speed.

Calculations were therefore needed as checks on the elevator, the wing, and the fin, apparently in that order of priority.

2.4 Calculations Based on Ground Resonance Modes

It proved difficult to excite and record sufficient modes in the ground resonance tests to form the basis of satisfactory flutter calculations and it was not until early 1954 that the first batch of calculations were finished. These calculations apparently confirmed the flutter model results for the elevator, wing and fin flutter speeds. The fin calculations were rather rushed, being, it was thought, the least important of the considerable amount of work in hand. In particular, no allowance was made in these calculations for the aerodynamic effect of the dihedral of the tailplane. The apparent agreement of the calculations with the flutter model results appeared to justify this simplification.

2.5 Accident to 1st Prototype

In May 1954 the elevator operating circuit on the 1st Prototype was stiffened, to increase the flutter speed, and corresponding increases in the cleared speed were allowed. The speed increases were made under the control of rudder and elevator jerk tests. The elevator jerk responses showed heavy damping in the mode forced. The responses to rudder jerks were difficult to understand. In all only thirteen records were obtained at different speeds, at low altitude and at high altitude. In three of these records, the trace appeared to show large damping at high amplitudes followed by lower damping at smaller amplitudes. The frequencies were sensibly constant. Two of these records were taken at high altitude, where the trace at the highest speed reached showed a simple heavily damped oscillation. The other was taken at just below the maximum speed allowed at low altitude. This showed a value of 2% of critical damping over the lowly damped, small amplitude part of the trace. Another flight up to the maximum permitted speed failed to give any results because of an instrumentation failure. No explanation of the apparently dual damping characteristic and random occurrence of these traces could be found, but it was thought at that time that, even if the damping of the small amplitudes was significant, a value of 2% of critical damping was an indication of adequate safety. There seemed no reason therefore to reduce the already restricted speed further, especially as flight up to the maximum allowed speed had been made without incident.

Further rudder jerk tests were planned in an attempt to clarify the position, but before these were done the first Prototype crashed when engaged in position error tests at low altitude (in July 1954). The speed at which it was flying was known to be the speed at which 2% of critical damping had been recorded two weeks previously. The tailplane became detached by a failure at the top of the fin.

2.6 Reasons for 1st Prototype Accident

Fin flutter or some forced oscillation was soon indicated as a reason for the accident. Eyewitnesses reported low frequency oscillations of the tail unit, and large static loads were ruled out by the observed straight and level flight of the aircraft just before the fin failure. It was difficult to understand, however, how flutter had occurred when both model tests and calculations showed very large margins of safety and when flight at higher speeds had been safely achieved several times. No system of fin oscillations forced by the rudder or elevator power control units could be devised, in spite of considerable efforts.

The cause of the accident was not revealed until several months later, when stiffness tests on a complete test tail unit structure showed hitherto unsuspected flexibilities over the fin-tailplane junction. These flexibilities were not noticed during the initial stiffness tests on the tail unit because, in these, the fin was tested without the tailplane being assembled on it, and so no loads were applied to the fin-tailplane junction.

The flexibilities were introduced into the flutter model in rather a crude fashion, but which served to indicate that they would have reduced the fin flutter speed considerably. Thus the flutter model showed that the fin flutter speed was a great deal lower than the original estimates. It remained to show why the calculations based on the ground resonance modes had also given too high a critical speed. The omission of the aerodynamic effects of tailplane dihedral was the obvious starting point, and when this omission was remedied, the calculated flutter speed also dropped considerably. It therefore appeared that results from both model and calculations were consistent with fin flutter being the cause of the accident. This still did not explain why an accident had occurred at a speed which had been exceeded several times without incident. The most likely explanation lies in a group of bolts in the fin-tailplane junction which were found in the wreckage to have failed in fatigue. These fatigue failures had no appreciable effect on the overall strength of the tail unit, but it is likely that they reduced the stiffness slightly. This was sufficient to bring an already low fin flutter speed below the maximum permitted speed.

2.7 2nd Prototype Fin Flutter Calculations

With the 1st Prototype accident apparently explained, the main object of the flutter work was the clearance of the fins of the 2nd Prototype and production aircraft. The 2nd Prototype fin was stiffened considerably by modification to the fin-tailplane junction and the production aircraft fin was slightly shorter and of a different, stiffer, type of construction.

It was soon found that the aircraft fin-tailplane junction could not be represented perfectly with the simplified form of construction of the model. The model was, however, modified to give a better representation than had been achieved in the initial

lap tests (see Section 3). The emphasis now lay on the calculations based on the aircraft ground resonance modes in which the actual structure inherently manifested itself. These calculations based on 2nd Prototype modes were finished late in 1955. They gave a fin flutter speed three times that found in the 1st Prototype work, indeed of the 20% increase suggested by flutter model tests.

Detailed comparison of the 1st and 2nd Prototype calculations showed that most of the large increase in fin flutter speed was due to a difference in the aerodynamic stiffness coupling term between the fin bending and fin torsion modes. This term depended mostly on the aerodynamic incidence of the tailplane in these two modes and these incidences proved to be very small - so small, in fact, that the inevitable inaccuracies in a ground resonance test made their precise value extremely uncertain. The apparent agreement between the calculated fin flutter speed for the 1st Prototype and the accident speed could therefore only be attributed to a coincidence and it was reluctantly conceded that ground resonance modes were useless for the estimation of a fin flutter speed. The position at the end of 1955 was, therefore, that the flutter model was the only source from which estimated fin flutter speeds could be obtained. As it was known that the model could not be made completely representative of the aircraft, some link was required between the model, which gave the effect of aerodynamic forces correctly, and the aircraft, which gave invaluable information about its structure in ground resonance tests, albeit in a somewhat enigmatic form. This link could be provided by calculating the aircraft normal modes and then using those modes as a basis for flutter calculations. These calculations, described in Section 4, were required urgently as, by then, production aircraft fins were being made. The emphasis was therefore on speedy results.

3. FLUTTER MODEL TESTS

3.1 Introduction

Most of the early flutter model test programme was concerned with elevator flutter. After the accident, however, fin flutter became the main concern, and it is the fin flutter tests which are described here.

3.2 Model Construction

The flutter model represented the rear fuselage and the tail unit (see Figure 2). The structure of the aerodynamic surfaces of the tail unit was represented by single metal spars to which were bolted wooden boxes giving the shapes of the surfaces. These boxes were ballasted to give the required mass distribution.

It was obvious that the single spar construction (a true 'flexural axis') could not be made to represent exactly the low aspect ratio fin, but it was intended to base the model tests with calculations based on modes measured in the aircraft ground resonance tests in which, of course, all the effects of the aircraft structure would be included. After the accident and the stiffness tests on the test tail unit, however, it was obvious that the original model structure was seriously deficient in representing the fin-tailplane junction. A closer representation was obtained in 1956 by fitting a set of gimbals between the fin and the tailplane spar. The rotations of the gimbals were controlled by torsion bar springs, thus giving

discontinuities in the angular deflections in roll and yaw at the fin tailplane junction. Even this did not represent the aircraft structure exactly, in that the aircraft showed cross stiffnesses between roll and yaw in the junction. To achieve this on the model would have meant tilting the gimbals and was considered to be too complicated.

3.3 Model Tests

The flutter model results for fin flutter were confused by two unexpected features:-

- (a) It was found that the fin flutter speed depended critically on the steady tailplane airload. Part of this effect was undoubtedly due to the change of tailplane dihedral under the airload, since it had already been found that dihedral affected the fin flutter speed. The magnitude of the tail load effect, however, suggested that there was also some additional purely aerodynamic influence.
- (b) The dependence of fin flutter speed on tailplane dihedral gave rise to further complications because the optimum model linear and velocity scales inevitably led to a discrepancy between the model and aircraft Froude numbers. This meant that the model in the wind tunnel was similar to the aircraft in a much larger gravity field, and so with an effectively reduced dihedral. Thus to interpolate for an aircraft in a 1g gravity field, the model had to be tested upside down.

Figure 3 shows how fin flutter speeds with the model the right way up and upside down and with several different airloads had to be plotted before a fin flutter speed for zero airload and at 1g could be extracted for each stiffness configuration.

With this standard fin flutter speed for each stiffness configuration (i.e. with change of fin spars and gimbal springs) there still remained the problem of interpolating for an aircraft stiffness. The method finally adopted was to plot the model fin flutter speed (reduced to zero tail load and aircraft 1g) against the overall fin torsional stiffness, i.e. the stiffness about the fin spar between the fin root and the tailplane root, the discontinuities across the fin-tailplane junction being included. Figure 4 shows that a reasonable connection between fin flutter speed and this stiffness was established.

The equivalent aircraft stiffness could be found from the results of stiffness tests. This value, of course, included the cross stiffnesses at the fin-tailplane junction. However, as these cross stiffnesses had not been included in the model tests used in establishing the torsional stiffness criterion, the applicability of the model results to the aircraft stiffnesses could not be guaranteed.

Ground resonance tests were also carried out on the model in the hope that the results from these would assist in the problem of deciding which model stiffness configuration was most representative of the aircraft. It was found that one mode only was appreciably altered by the changes in fin-tailplane junction stiffnesses and that was the fin torsion mode. This fin torsion mode was characterised by a nodal line lying just aft of the fin leading edge. There was considerable motion of the tailplane and, in fact, most of the kinetic energy in the mode was due to

tailplane motion. The inertia forces arising from the tailplane motion had, of course, to pass through the fin-tailplane junction. It was found that there was a connection between the frequency of the fin torsion mode and the fin overall torsional stiffness (see Figure 5).

The results of the flutter model tests are compared with the results from calculations in Section 6.1.

4. CALCULATIONS

4.1 Introduction

The calculation of normal modes and, from them, flutter speeds was started very late in the development of the aircraft. The need for such calculations is discussed in Section 2.7. The calculations had to represent the flutter model and the aircraft with the insertion of suitable sets of data. The mass and stiffness distributions of the model were known accurately and so the comparison of calculated and measured resonance modes of the model would check the form of the calculation. The comparison of calculated and measured flutter speeds of the model would check, particularly, the aerodynamic data.

The mass and stiffness distributions of the aircraft could, it was hoped, be adjusted so that agreement was obtained between the ground resonance modes calculated for and measured on the aircraft. The use of the calculated modes with aerodynamic data, checked at low Mach number against model tests, should lead to the calculation of accurate flutter speeds.

4.2 Form of Calculations

The method of calculation decided upon was of the 'branch mode' type. Branch modes are here defined as the normal modes obtained when only one component is flexible and the rest of the aircraft is rigid and clamped at a suitable point. The lowest frequency branch modes are coupled together to give the normal modes of the complete aircraft. In this way the important low frequency aircraft modes can be found by solving several comparatively small-order normal-mode problems rather than one much larger one. The resulting reduction in computation becomes more important if it is found that the calculations have to be repeated, for instance with modified stiffness data.

4.3 Details of Calculations

The 'discrete mass' method was used to compute the branch modes of each component. The structural representation of the aerodynamic surfaces was based on the flexural axis concept. This was done mainly because it was intended to vary the stiffnesses in order to get better agreement with the aircraft ground resonance test results. With a flexural axis it would be possible to keep bending and torsion effects separate (by starting with, for example, elevator bending branch modes and elevator torsion branch modes) and yet keep perfect physical consistency. If structural influence coefficients found from a strain energy approach had been used, the only possible rapid variation of stiffness possible would have been an overall factor on all the stiffnesses

of each component. The application of selective factors to a consistent set of influence coefficients would have involved the risk of introducing a physical inconsistency that could have upset the large scale computations intended. As stiffness tests had been carried out on most of the full scale components, it was hoped, by checking against test results, to make the flexural axis representation adequate, at any rate for most of the important stiffnesses.

In particular, by including separate branch modes for the rigid rotations in roll and yaw of the tailplane relative to the top of the fin, the model direct stiffnesses and the aircraft direct and cross stiffnesses over the fin-tailplane junction could be introduced at will.

Throughout, strip-theory aerodynamics for $M = 0$ was used. Previous work had indicated that this would be adequate for the air forces on the tailplane and elevator. It was hoped that it would also be adequate for the lower aspect ratio fin, which had, of course, an end-plate effect added by the high set tailplane.

4.4 Scope of the Calculations

Both the symmetric and antisymmetric cases were covered. Only the antisymmetric calculations, including the important fin flutter work, are described here. The aircraft was divided into 80 discrete masses. Within this framework, eight sets of branch modes in up to 16 degrees of freedom were computed. From these, 24 modes with frequencies up to 30 c/s were retained in the calculation of the aircraft normal modes. Initially, the first 15 aircraft normal modes (with frequencies up to 20 c/s) were used in a flutter calculation, the solution being obtained on a digital computer. This was done to avoid the possibility of introducing errors of omission by selecting six modes, the maximum that could be solved on the analogue computers available. In fact it was found, by comparing solutions against the large case, that selections of six aircraft normal modes sufficed for a good approximation to flutter speed.

In the calculation for the production aircraft, the aircraft normal modes were computed three times, in attempts to obtain better agreement with the modes measured in the ground resonance tests. In general, reasonable agreement in both frequency and modal shape was ultimately achieved, except for one important mode, the fin torsion mode. This feature is discussed in Section 6.1, where the results of the calculations are compared with flutter model results.

5. FLIGHT FLUTTER TESTS

5.1 Introduction

During the development of the flutter model tests and flutter calculations described in Sections 3 and 4, it became obvious that full scale flight flutter tests were going to be essential for the final flutter clearance of service aircraft to the design diving speed. Some of the reasons are:-

- (a) The model tests were at low Mach number and, as the calculations described in Section 4 were started so late in the development of the aircraft, there was not sufficient time to consider anything but the incompressible derivative case. There was, therefore, no information about Mach number effects on fin flutter.

- (b) Model tests had shown that the fin flutter speed was critically dependent on the steady airload on the tailplane. Part of this effect resulted from the change of dihedral due to the tail load and part from additional oscillatory aerodynamic forces acting when a steady airload is present. If attempts had been made to extend the calculations to check the overall effect, the first part would have been lengthy and the second uncertain. It was therefore decided to rely on flight tests for the check.
- (c) It transpired that both the calculations and the flutter model tests failed to give agreement with the aircraft ground resonance tests in the important fin torsion mode. While the nature of the discrepancy implied that the estimates of fin flutter speed would be conservative, if anything, a full scale flight check of fin flutter speed was sorely needed to give confidence to the estimates of fin flutter speed of service aircraft.

The information required from the flight tests was therefore concerned, not with a formal demonstration of adequate damping up to the design diving speed, but with the comparison of extrapolated fin flutter speed in different conditions so that the effect of Mach number, tailplane airload and fin stiffness changes could be inferred. That is to say, the flight tests, in order to be of any use, had to be taken to the point at which flutter conditions were clearly shown.

The bulk of the flight tests were carried out on the 2nd Prototype. Tests were made at high and low Mach number with the aircraft in its standard condition and with both ailerons rigged in an up position. This latter condition altered the airload distribution on the sweptback wing and consequently altered the airload required from the tailplane to trim the aircraft. Thus the effect of tailplane airload on fin flutter speed could be found. Re-rigging of the ailerons was preferred as a method of changing the tailplane load because it gave a much larger change than the obvious method of altering the aircraft centre of gravity. The ailerons were rigged up to increase the upload on the tailplane, so reducing the fin flutter speed. This was done to make sure that the modified fin flutter speed was still within the permitted speed range of the aircraft.

5.2 Test Technique

By the time the flight tests on the 2nd Prototype began, much of the flutter model work described in Section 3 was finished, and some early results from the calculations of Section 4 were available. The comparison of the results with the very few rudder jerk responses obtained on the 1st Prototype just before the accident (see Section 2.5) seemed to indicate that the calculations and the flutter model did not give the same sub-critical response as the aircraft. To make sure that the critical mode was being monitored in the flight tests, it seemed necessary to force all the modes that might be significant to fin flutter. We had experience of how concentration on one feature might lead to trouble with an unexpected feature and so all the modes significant to elevated flutter (symmetric and antisymmetric) were also to be monitored.

The forcing of all these modes required a controlled excitation rather than the simple excitation given by a control surface jerk. An added reason for controlled excitation was that the analysis of the few 1st Prototype rudder jerk responses had seemed to indicate that reliance on these responses was positively dangerous in that the rudder jerk forced predominantly a non-critical mode, with the critical mode

being shown only a few knots before flutter. The tests were therefore started with rotating out-of-balance inertia exciters. Three exciters, one to give a vertical force and two to give lateral forces, were carried. The vertical exciter had a static out-of-balance of 60 lb/in. to be used at frequencies between 1/5 c/s and 12 c/s, while the lateral exciters had static out-of-balance moments of 360 lb/in. and 80 lb/in. respectively. The larger exciter was for use from 1.5 c/s to 4 c/s and the smaller from 3 c/s to 12 c/s.

The exciters were accelerated automatically through the frequency ranges and the continuous responses of fifteen pick-ups attached to the tail unit during the frequency sweep were recorded.

In addition, each mode was tuned from the cockpit and the decays after a sudden stopping of the exciter were recorded.

The responses were monitored by plotting the amplitude of each pick-up in each mode against speed and also the damping of each mode against speed.

Much interference was caused by air turbulence. The maximum amplitudes forced by the exciters were of the order of ± 0.2 in. at the tailplane tip and, so that these amplitudes should be clearly visible on the records, very smooth air was required. A large proportion of the early records proved useless because the forced responses were obscured by turbulence. To reduce the flying time, the frequency sweeps were discontinued after a time. Even when records of the responses in these sweeps were obtained in smooth air, the reduction of results with the unavoidably varying calibrations of the recording equipment showed much scatter in the plots of amplitude against speed and it was felt that such plots would be of little use in the extrapolation to a flutter condition. The plots of damping against speed showed little scatter for the high frequency modes (both symmetric and antisymmetric), but it was not possible to put quantitative values to the damping of the two lowest frequency fin modes. These modes occurred at about 2 c/s and 3 c/s and the amplitudes forced in these modes, even by the exciter with 360 lb/in. out-of-balance, were only about twice the general level of turbulence in the smoothest air. The decays in these modes lasted only about two cycles before merging into the background turbulence.

Accurate estimates of damping were therefore not possible, but it was argued that the decays showed at least 6% of critical damping, (i.e. about 2 cycles to half amplitude) and that accordingly small increases in speed could be allowed while this state of affairs prevailed. It was reasoned that as soon as the damping started to reduce below 6% of critical it would become possible to analyse the results quantitatively. Speed increase of about 3% of the estimated fin flutter speed were allowed on the results of the tests up to a speed just below the estimated flutter speed. Up to this speed the damping of the higher frequency modes was increasing steadily, but no idea of the variation of the damping of the two fin modes with speed was obtained. However, a close study of the records indicated that the lowest frequency fin mode (at about 2 c/s) was beginning to change at the highest speeds reached. There was a small, but repeatable, change in frequency with speed and the response to random turbulence showed a larger proportion of the 2 c/s mode than at lower speeds. It was an obviously undesirable state of affairs to suspect that, within a few per cent of a calculated fin flutter speed, the vital fin was changing significantly as the speed increased and yet not to have any knowledge of the variation

of damping with speed. In an attempt to supply this information rudder kick responses were resorted to, in spite of the conclusions from the 1st Prototype records that they might contain misleading information. It was known that rudder kicks forced much larger amplitudes than the exciters (about $\pm 1\frac{1}{2}$ in. maximum) and this level of amplitude should ensure freedom from interference from turbulence. The rather alarming results obtained from the analysis of rudder jerk responses are shown in Figure 6. Although the deduction from the inertia exciter forced records that the damping was above 6% of critical was correct, the much larger amplitude rudder kick responses enabled larger values of damping to be estimated and these showed that rapid reduction of damping started about 15% below the extrapolated fin flutter speed. Figure 6 is based on a large number of rudder kick responses. A small proportion of these responses was very similar to those recorded on the 1st Prototype (see Section 2.5) from which a plausible conclusion had been drawn that rudder kick responses need not show the critical fin mode clearly. It was clear from the 2nd Prototype records that this type of trace was due to interference from air turbulence. The 2nd Prototype records were also analysed for frequency and modal shape. This analysis showed clearly that, throughout the speed range, the rudder jerks forced one mode predominantly and that this mode became the critical fin flutter mode.

The tests so far described were at low Mach number. Once it had been established that rudder kicks excited clearly the critical fin mode, further tests at high Mach number and at both high and low Mach number with the ailerons rigged up proceeded quickly, with rudder kick responses being used to monitor the fin flutter mode and decays from tuned resonances forced by the inertia exciters being used to monitor the elevator modes.

About 120 hours flying time was spent in the 2nd Prototype flight flutter tests. Of this about 40 hours were wasted because air turbulence obscured the records, 16 hours were spent in the initial recordings of frequency sweeps, 36 hours in obtaining decays from resonances tuned with the inertia exciters and 28 hours in obtaining rudder kick responses.

5.3 Results from 2nd Prototype Flight Flutter Tests

The fin flutter speed extrapolated from the low Mach number tests is compared with the estimates in Section 6.2.2. The comparison of the extrapolated fin flutter speeds at high and low Mach numbers showed that at $M = 0.90$ the critical speed was 12% less than that at low Mach number.

The comparison of test results at low Mach number with the aircraft in its standard condition and with the ailerons rigged up showed that the variation of fin flutter speed with tail load observed in the flight tests agreed with that observed on the flutter model.

5.4 Results of Flight Tests with Production Aircraft

The fin for production aircraft was initially designed before the model tests described in Section 3 and the calculations described in Section 4 were completed. With the results of the model tests and calculations, it was felt necessary to increase the stiffness of the fins of production aircraft. However, several aircraft were completed with the initial fin design. One of those was used for further flight

flutter tests. This was done because the very rapid approach to fin flutter made it unlikely that the stiffer fin of production aircraft would reveal the approach to a flutter condition in flights up to the design diving speed, and it would have been difficult to arrange for the aircraft to fly faster than this.

Since a check was required on the fin flutter speed of production aircraft to ensure that the estimates gave good results for the changed geometry and stiffness distribution of the aircraft, this could only be achieved by testing an aircraft with the more flexible fin. These tests, in fact, just indicated a fin flutter condition, at a speed 10% greater than the design diving speed in flights up to the design diving speed. The flight test results are compared with estimates in Section 6.2.2.

6. CORRELATION

6.1 Comparison of Flutter Model Results and Calculations

In Section 3 it is explained how the flutter model results for fin flutter speed and for fin torsion mode frequency showed a reasonable relationship with the overall fin torsional stiffness. The results from model tests and the calculations are best compared on the basis of these graphs.

Figure 7 shows the comparison of flutter speeds for the prototype geometry. Of the three calculated values shown, the 'model case' was with a structural representation very close to one of the model configurations, whereas the 1st and 2nd Prototype calculated values included stiffnesses to give a close approximation to the stiffness test results on these aircraft. In particular, cross stiffnesses between roll and yaw were inserted into the fin-tailplane junction. Figure 7 shows that the effect of these cross stiffnesses on the overall torsional stiffness was shown up by variations in flutter speed similar to those obtained from the model tests in which the overall torsional stiffness was altered by changing the direct stiffnesses in the junction. Thus the original doubt as to the applicability of the model test results to the aircraft structure was resolved. Figure 7 also shows that, as well as the variation of the fin flutter speed with fin torsional stiffness, the actual flutter speeds from the model tests and the calculations were in good agreement. Figure 8 shows the comparison between fin flutter speeds from model tests and from calculations for the production aircraft geometry, both plotted against fin overall torsional stiffness. Again reasonable agreement was found. The calculated point at the lowest stiffness was intended to represent the initial fin design. The other calculated point was with a more or less arbitrary increase in stiffness, applied in order to observe the effect of fin stiffness increases.

Figure 9 shows the comparison between model and calculated fin torsion mode frequencies, again plotted against overall fin torsional stiffness. It may be seen that there is reasonable agreement.

6.2 Comparison of Estimates and Aircraft Test Results

6.2.1 Ground Resonance Tests

In the prototype calculations, there was fair agreement in calculated modes and measured aircraft resonance modes, except in the fin torsion mode. It was thought

that this might have been due to the absence of the wing in the calculations, the wing fundamental being close in frequency to the fin torsion mode. However, the same discrepancy occurred in the calculations for the production aircraft, in which the wing and all the body freedoms were included. The extent of the discrepancy is shown on Figure 9, where the frequencies of the fin torsion modes measured on aircraft with the initial and final version of the fin are shown. The stiffnesses of these fins was measured in stiffness tests. It may be seen that the frequencies of the fin torsion modes of the full scale aircraft are considerably higher than would be given by the interpolation of the model test results and calculations with the aircraft fin stiffness values.

In Section 6.1 it is shown that there was good agreement between model tests and calculations for the relationship between both fin flutter speed and fin torsion mode frequency when plotted against fin torsional stiffness. Naturally, cross plots of these results would have given equally good agreement with fin flutter speed plotted against fin torsion mode frequency. However, because of the discrepancy between the estimated and full scale tests for the fin torsion mode frequency with the same value of fin torsional stiffness, very different fin flutter speeds are obtained for full scale aircraft, depending on whether fin torsional stiffness or fin torsion mode frequency is used as a criterion. The torsional stiffness criterion was preferred, until the flight flutter test results were available, as this gave conservative fin flutter speeds and because its application to the 1st Prototype gave a fin flutter speed low enough to attribute the accident to fin flutter.

6.2.2 Flight Flutter Tests

As described in Section 5, a series of flight flutter tests was taken to the point where fin flutter speeds were clearly indicated. From these results, it was possible to extract the effects of Mach number and tailplane airload on fin flutter speed. The application of these effects, appropriate to the flight test conditions, to the estimates of fin flutter speed from model tests and calculations (at zero Mach number and tailplane airload) gives values to be compared directly with flight tests results. This comparison, then, bears on the validity of the model test and calculated results, the other effects of Mach number and tailplane airload having been obtained from full scale flight tests. In the estimates, the fin torsional stiffness criterion was used. The comparison is shown in Table I, the fin flutter speeds being expressed as a fraction of that found in the 2nd Prototype flight tests at low Mach number.

TABLE I

<i>Test</i>	<i>Estimated Fin Flutter Speed</i>	<i>Flight Test Extrapolated Fin Flutter Speed</i>
2nd Prototype at low Mach number	0.96	1.00
Initial production aircraft fin at high Mach number	1.05	1.09

It may be seen that excellent agreement was obtained, not only in actual flutter speeds but also in the relative flutter speeds of different fins.

Thus, clearly, the fin torsional stiffness is the appropriate criterion for fin flutter speed. Use of the fin torsion mode frequency as a criterion for fin flutter speed would have given estimates of flutter speed about 40% higher than those quoted in Table I.

Why the use of an apparently close representation of the aircraft structure in the calculations should have failed to give the correct fin torsion mode frequency and yet succeeded in giving a good result for the fin flutter speed is not known. It seems certain that the reason must be, in some way, connected with the simplifications made in the structural representation of the fin, and, particularly, of the fin-tailplane junction. A possible clue has been noticed in the comparison of the shapes of the calculated fin torsion mode and that measured in the aircraft tests. In both modes the fin is distorted elastically and the tailplane deflects almost rigidly about the top of the fin. Most of the strain energy in the modes is due to the fin distortion and most of the kinetic energy is due to the tailplane motion. The deflected shapes of the fin are similar (with a nodal line just aft of the fin leading edge) but in the aircraft mode the nodal line suddenly sweeps aft at the top of the fin. The moment of inertia of the tailplane decreases as the axis of rotation sweeps aft from the vertical to the horizontal, the relative values being in the ratio three to one. Thus, if the fins had the same stiffness it would be expected that the aircraft mode would be of higher frequency, because the tailplane moment of inertia (about a more swept axis) is less. The sweep of the axis of rotation could be conceivably influenced by local details in the fin-tailplane junction under the influence of the tailplane inertia loads.

When air forces are present, the tailplane rolling motion is heavily damped, and the fin flutter mode is in good agreement in flight tests, model tests and calculations, all showing almost pure yaw of the tailplane. It is conceivable that the air forces, at speeds close to the critical speed, are much more powerful in deciding the movement of the tailplane than the local structure over the fin-tailplane junction and it is these air forces, similar in flight, in the wind tunnel and in the calculations, that fix the flutter mode more or less regardless of the type of structure over the fin-tailplane junction. This might explain why there is such good agreement in the flutter speeds. The argument is by no means wholly convincing, and some work is in hand to attempt to give quantitative backing to this idea.

A further discrepancy between aircraft test results and estimates occurred in the sub-critical dampings of the critical fin mode. Figure 10 shows that the calculations showed a gentle approach to the critical condition, that the flutter model approach was steeper and that the approach to flutter in the flight tests was very steep indeed. The differences between the model and the calculations could be due to the use of aerodynamic data in the calculations that was strictly applicable to sinusoidal motion. The further difference between model and aircraft could be due to the difference in fin torsion mode frequencies.

7. CLEARANCE OF SERVICE AIRCRAFT

The flight flutter tests on the 2nd Prototype and on a production aircraft with the initial fin design showed that the calculations and model tests gave accurate fin

flutter speeds and, more important, that the relative fin flutter speeds of different fins were accurately predicted (see Section 6.2.2). The flight flutter tests also gave the effect of Mach number on the critical fin speed and confirmed the model results for the dependence of fin flutter speed on steady tailplane airload (see Section 5.3).

The estimate of the fin flutter speed of service aircraft with the stiffened production fin could therefore be made with confidence. Because of the dependence of fin flutter speed on tailplane airload, the estimated fin flutter speeds varied appreciably with the position of the aircraft centre of gravity and in different manoeuvres. The minimum fin flutter speed occurs when the aircraft flies at maximum positive normal acceleration with its centre of gravity in the aftmost position. The estimates of this minimum fin flutter speed showed an adequate safety margin over the design diving speed, and service aircraft were finally given flutter clearance to the design diving speed some eight years after the initial flutter investigation on the tail unit was started in the design stage.

8. CONCLUSIONS

The purpose of this paper has been to describe briefly what is thought to be one of the few flutter investigations that have been taken to the point at which the results from low speed flutter model tests, from calculations and from aircraft tests on the ground and in the air can be compared directly. The bald facts arising from these comparisons are that the flutter speed was estimated with remarkable accuracy, but that the estimates for an important ground resonance mode and for the sub-critical response were shown to be considerably removed from the aircraft test results. There is little point in attempting to discuss the generality of these particular results.

Certain features of the techniques involved are, however, of general interest. These are with regard to the value of low speed flutter models and the safety aspect of flight flutter tests.

In the Victor flutter work low speed wind tunnel flutter models have proved invaluable. Their particular value, apart from a healthy breath of reality into the often foggy regions of a large scale flutter investigation, is the case with which critical parameters may be changed and their readiness to show features which would not otherwise have been investigated. An example from the Victor fin flutter investigation is the discovery from flutter model tests that the symmetric steady airloads on the tailplane have considerable effect on fin flutter speed. This would probably never have been looked for theoretically and, even if it had, the accurate determination of the magnitude of the effect presents almost insuperable difficulties.

To reduce the task of constructing the basic model and also of introducing changes, the model should be of a simplified form of construction. The correlation with aircraft tests should then be made through a calculation so planned that it can represent the model and also, by reasonably straightforward modifications, the aircraft. The form of calculation can be checked against the model results and the development to calculations for the aircraft can be made with confidence. An example here is the effect of body freedoms. These are a nuisance in flutter model tests, and in many types of main surface flutter they are not of major importance. Their absence from

the model would, however, make the check of the model mass and stiffness distributions by the comparison of model and aircraft ground resonance test results almost impossible. Body freedoms are, however, simple to put into a calculation. Therefore a calculation without body freedoms for the model and with body freedoms for the aircraft can bridge the gap between a simplified model (no body freedoms) and the aircraft.

It has been suggested that flight flutter tests are 'the most dangerous tests known to man'. That this is not necessarily so is shown by the Victor tests in which, in several test programmes, aircraft were deliberately taken to within a few per cent of a main surface flutter speed. It is not pretended that these tests proceeded quickly and without pauses for sober contemplation, but there were important reasons why fin flutter speeds had to be checked in the air and this was eventually accomplished quite safely. The essential, if obvious, point in flight flutter testing is that the magnitude of the speed increments allowed in the course of the tests must be decided with absolute confidence. This is likely to lead to much flight-testing time and requires comprehensive exciting and recording equipment. Whether this flying time and equipment development is worth while depends entirely on the confidence that can be placed on the flutter speed estimates.

In a properly controlled flight flutter test there cannot be any danger to an aircraft additional to that which is already there, because the carrying out of a flight flutter test cannot reduce the flutter speed of the structure. If the tests are carried out without due care and attention, they could prove dangerous, in that speed increases might be allowed without a critical mode being monitored, but even in this case, the danger is no greater than if the speed increases were allowed with no control at all.



Fig.1 The 'Victor' 1st Prototype

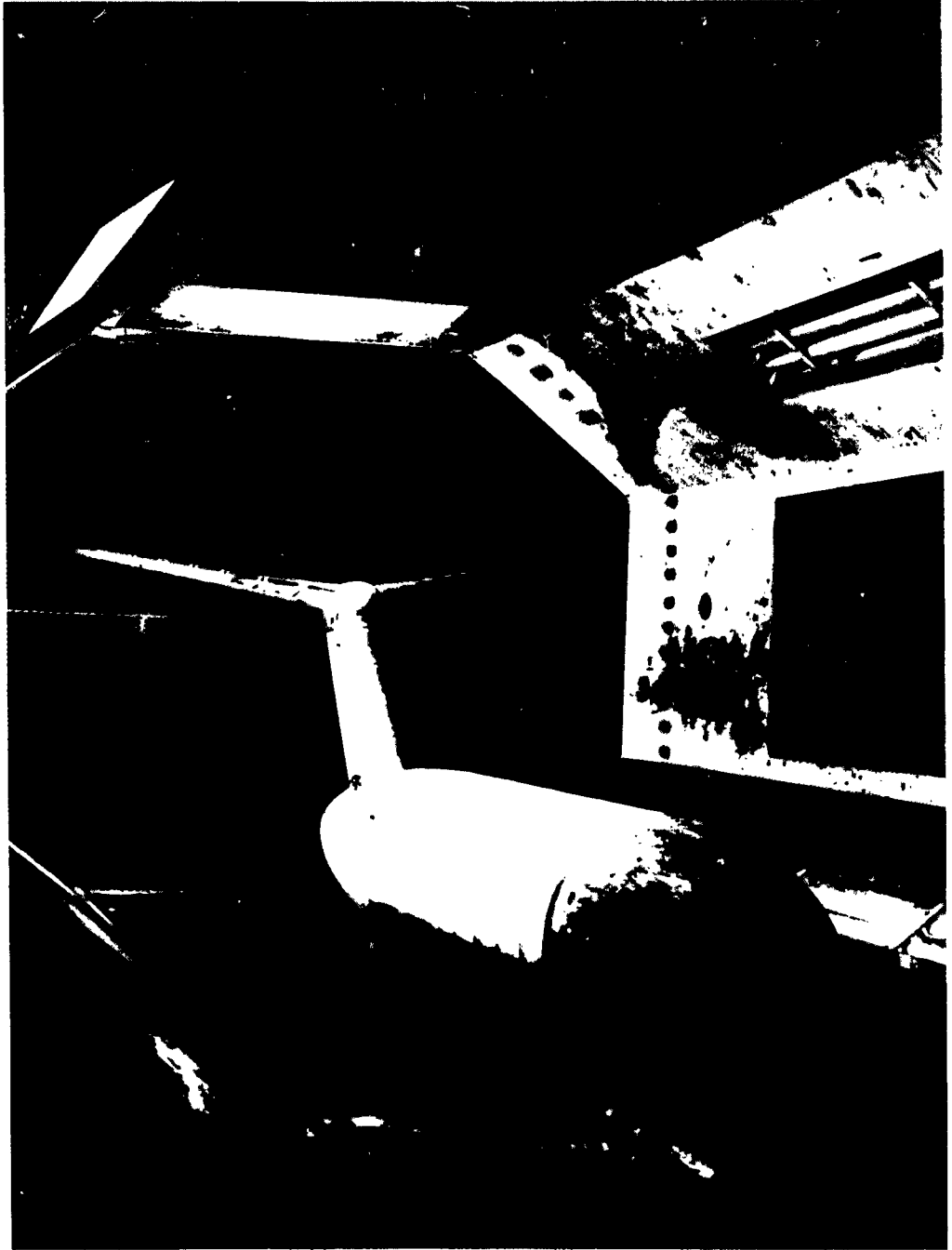


Fig.2 The tail unit flutter model in its original form

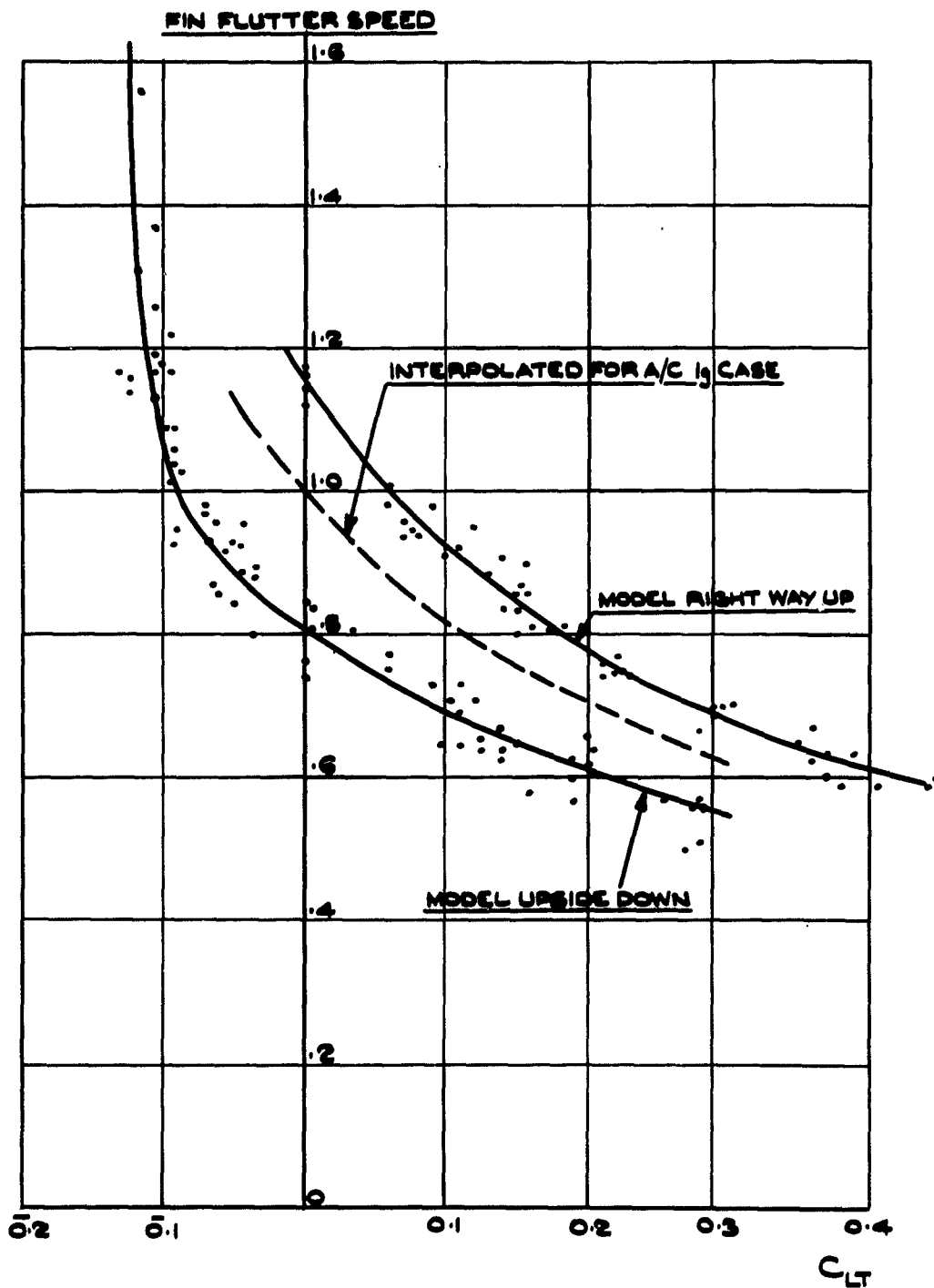


Fig.3 Flutter model results for fin flutter speed

X FIN SPAR A
 O FIN SPAR B

○ SCATTER OF RESULTS
 OBTAINED VIA FIG. 3.

FIN FLUTTER SPEED
 AT $C_{LT} = 0, A/C = 1$

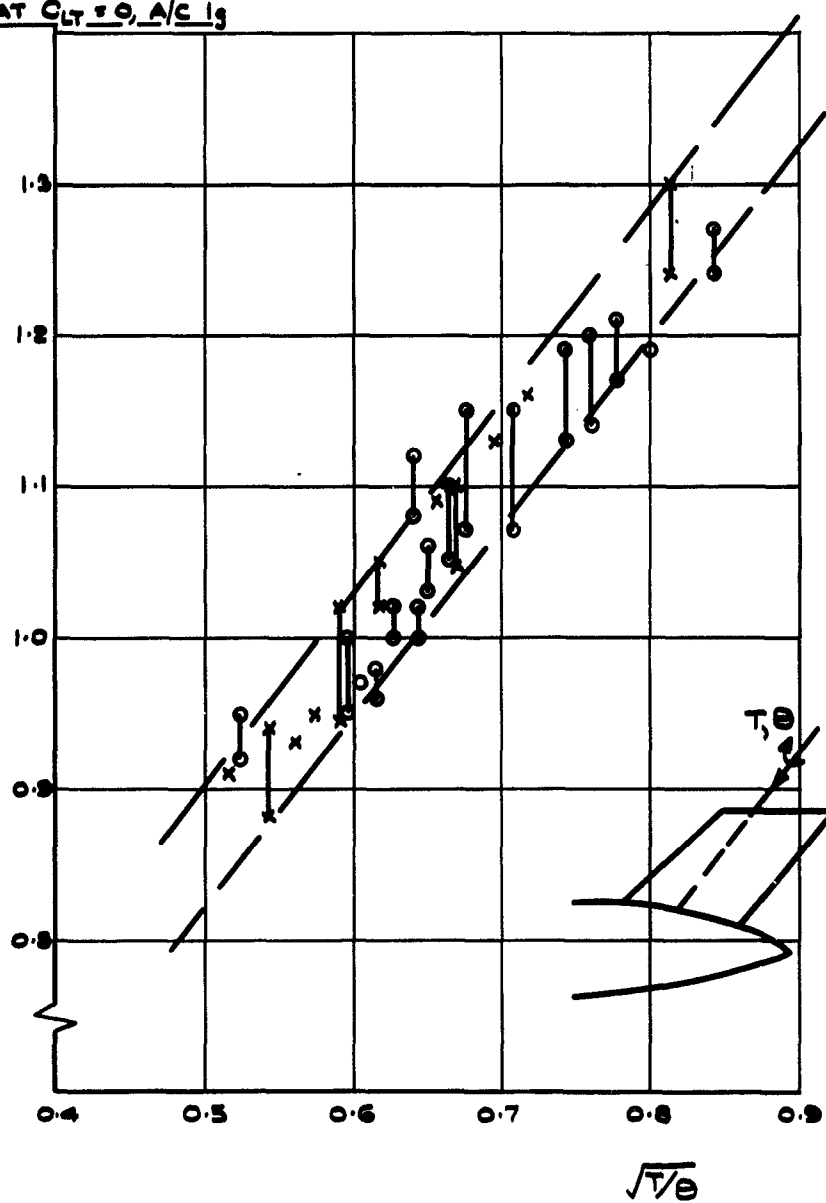


Fig.4 Fin flutter speed of flutter model prototype geometry

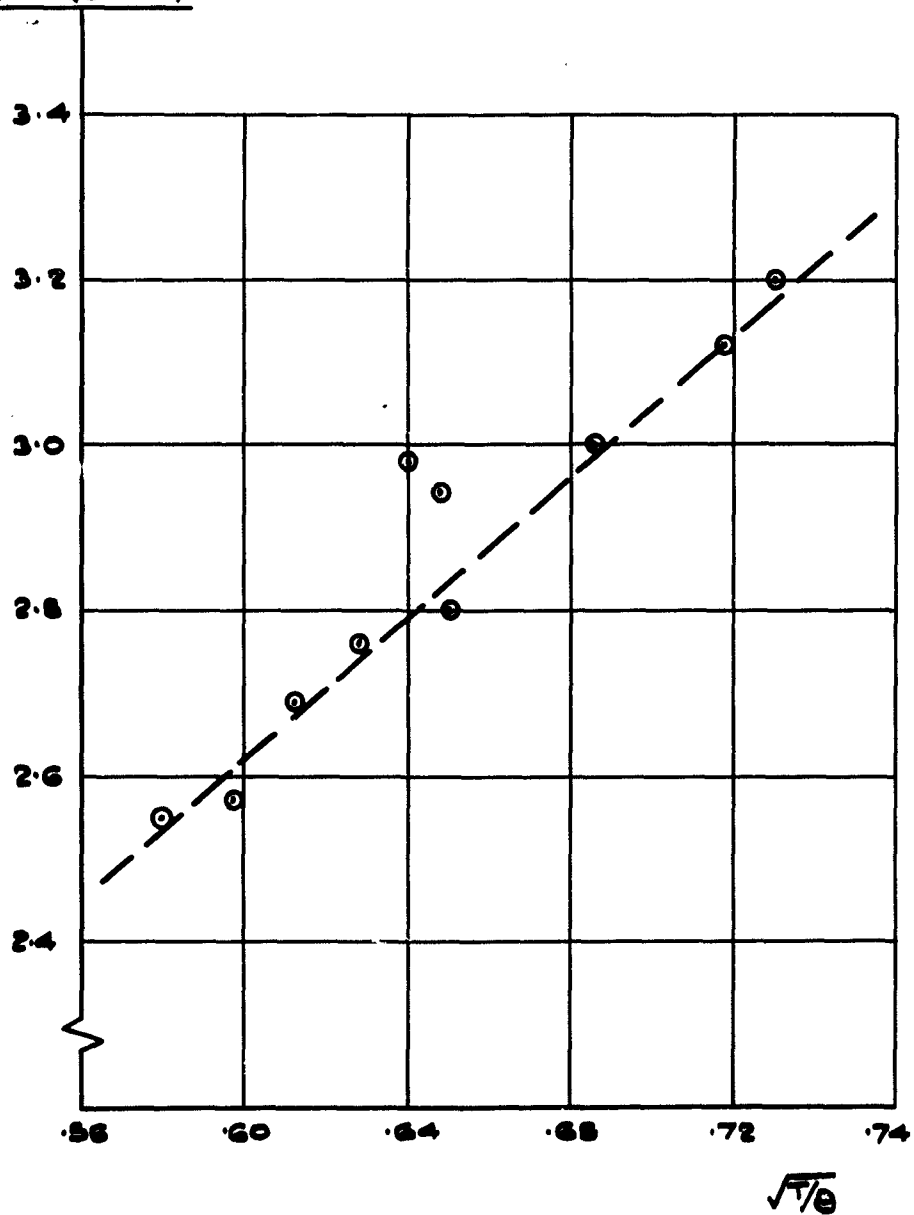
FIN TORSION MODE
FREQUENCY

Fig.5 Fin torsion mode frequency of flutter model. B.Mk.1 geometry

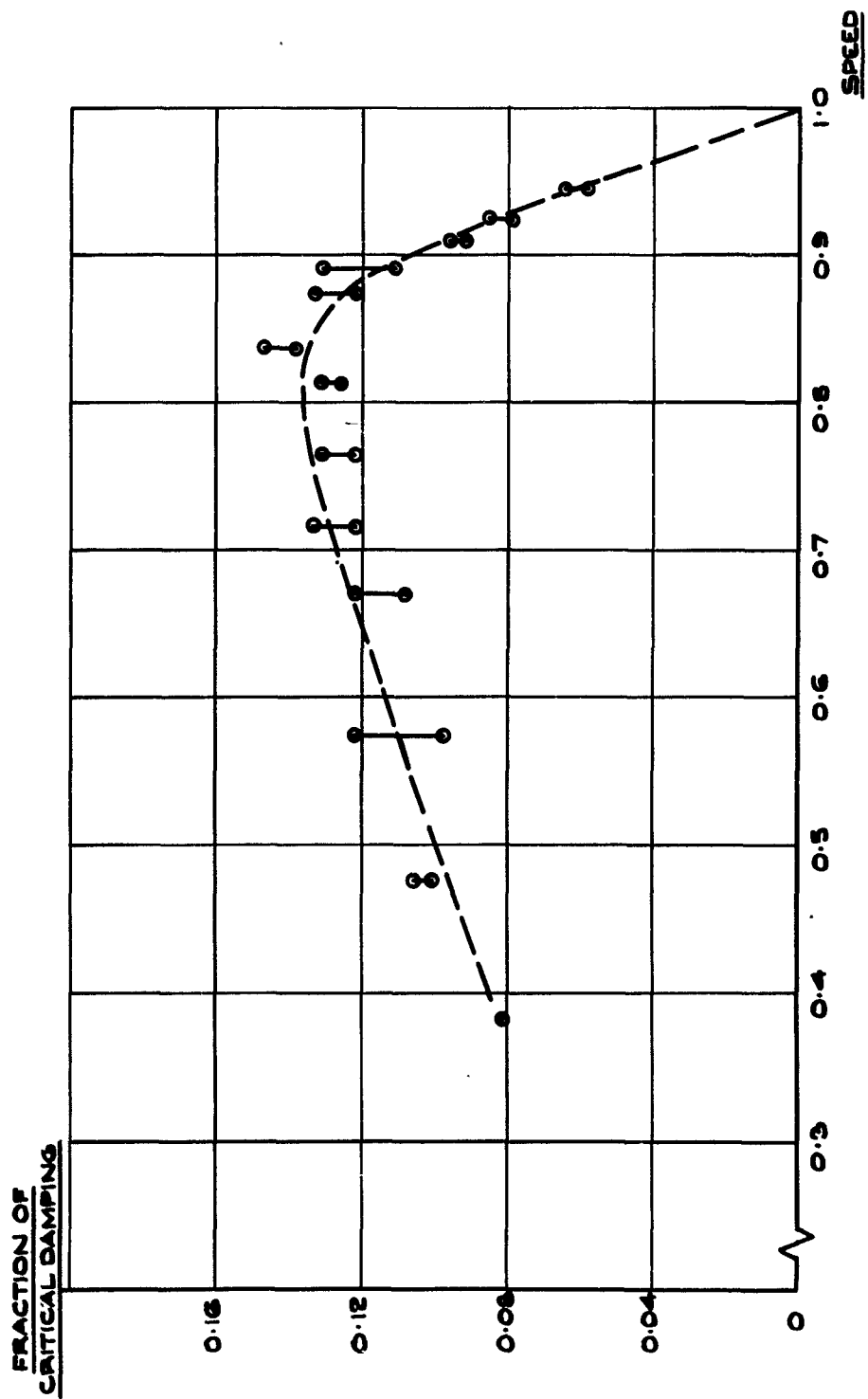


Fig. 6 Results of flight flutter tests on 2nd prototype at low Mach number.

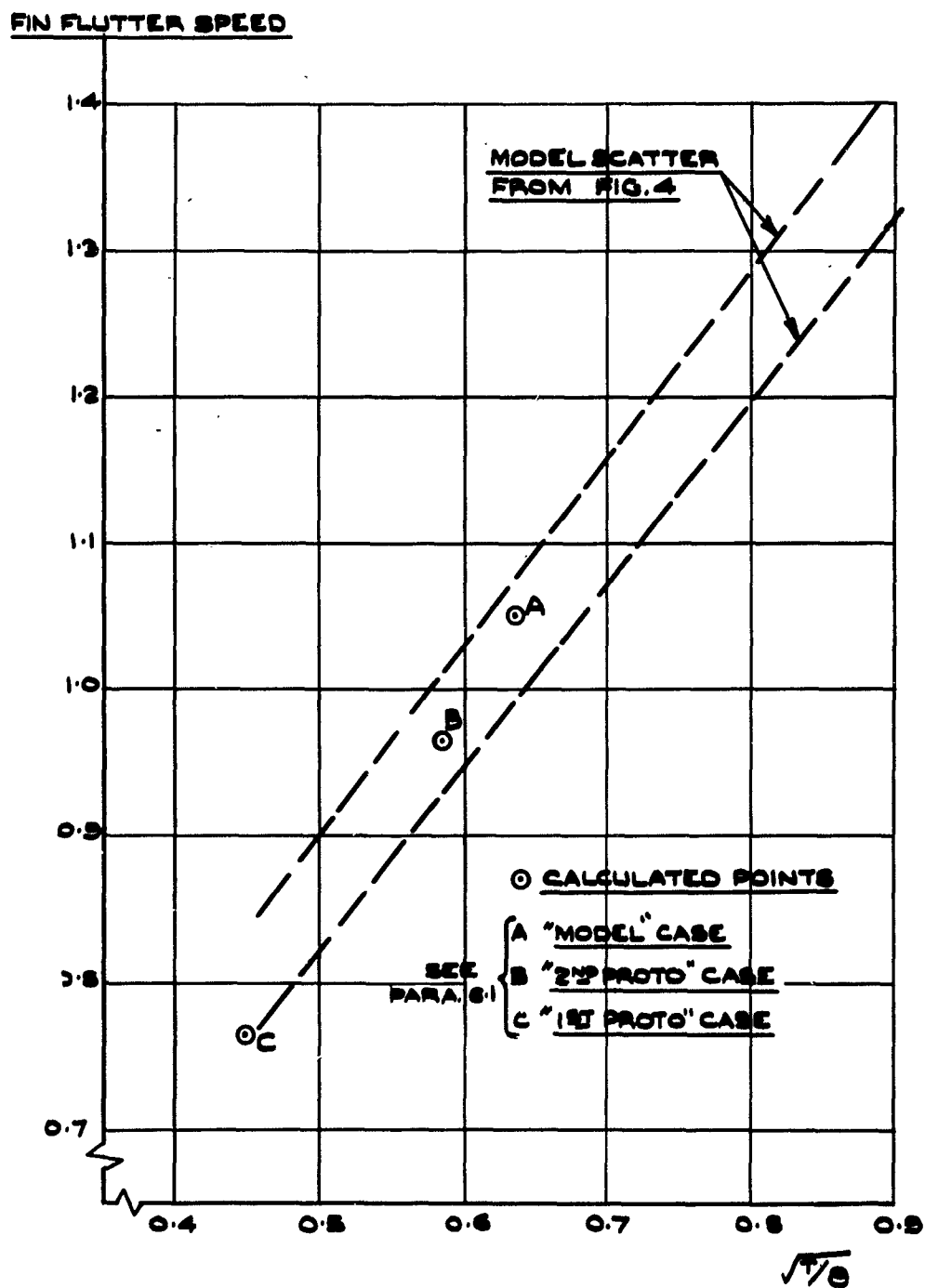


Fig.7 Comparison of model tests and calculations. Flutter speeds for prototype geometry

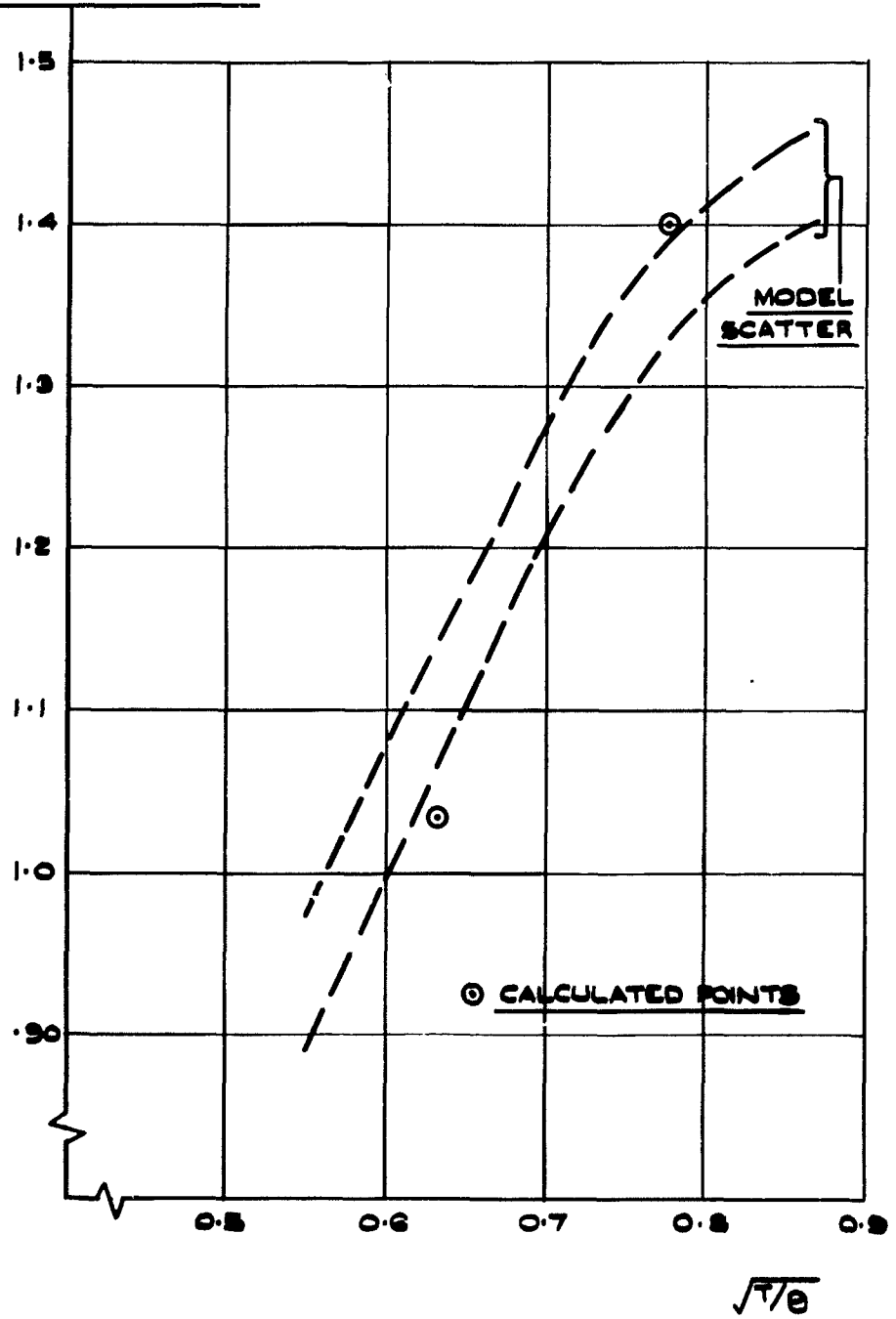
FIN FLUTTER SPEED.

Fig.8 Comparison of model tests and calculations. Flutter speeds for B.Wk.1 geometry

FIN TORSION MODE
FREQUENCY

○ CALCULATIONS

□ A/C TESTS

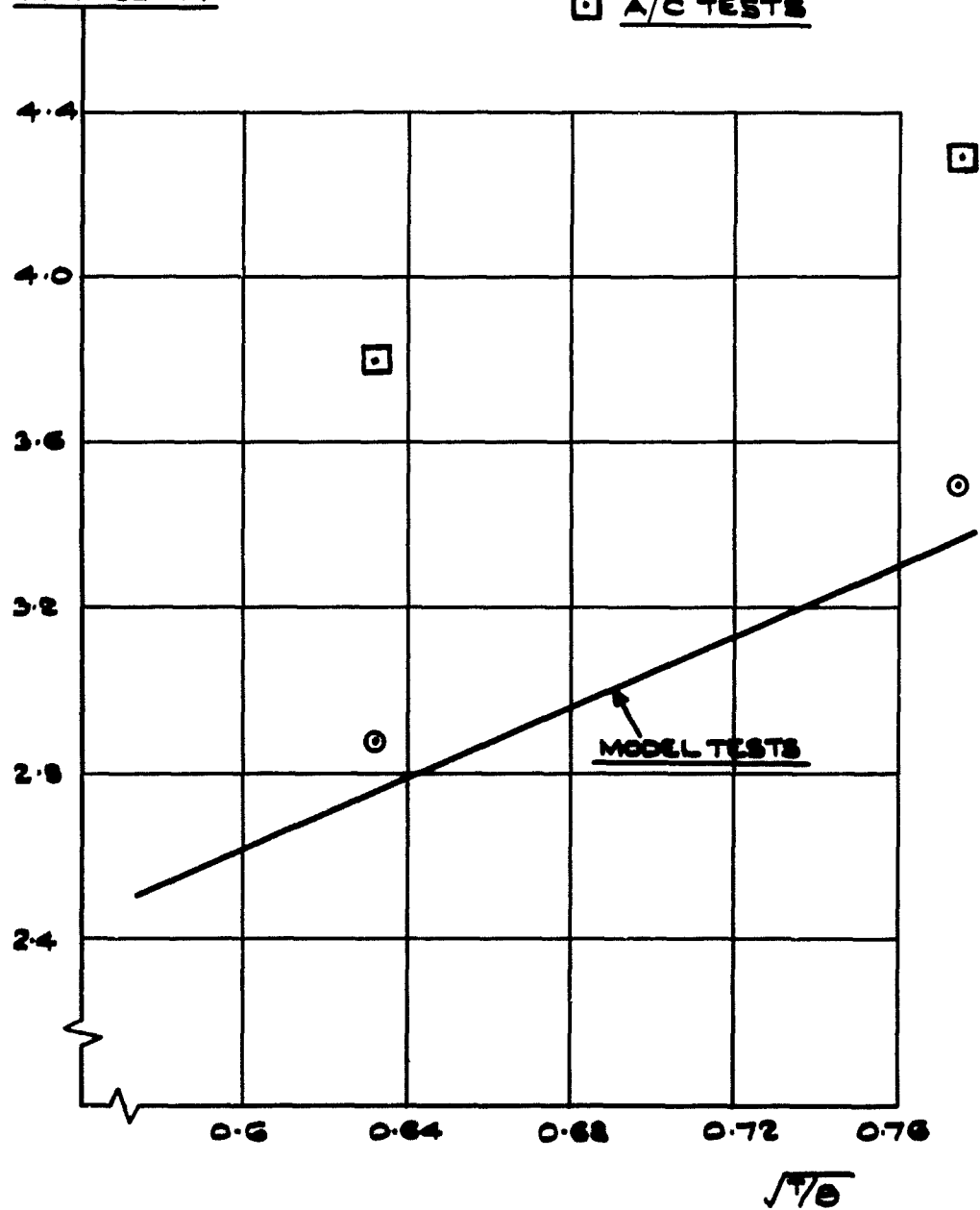


Fig.9 Comparison of model tests and calculations with aircraft tests. Fin torsion mode frequency for B.Mk.1 geometry

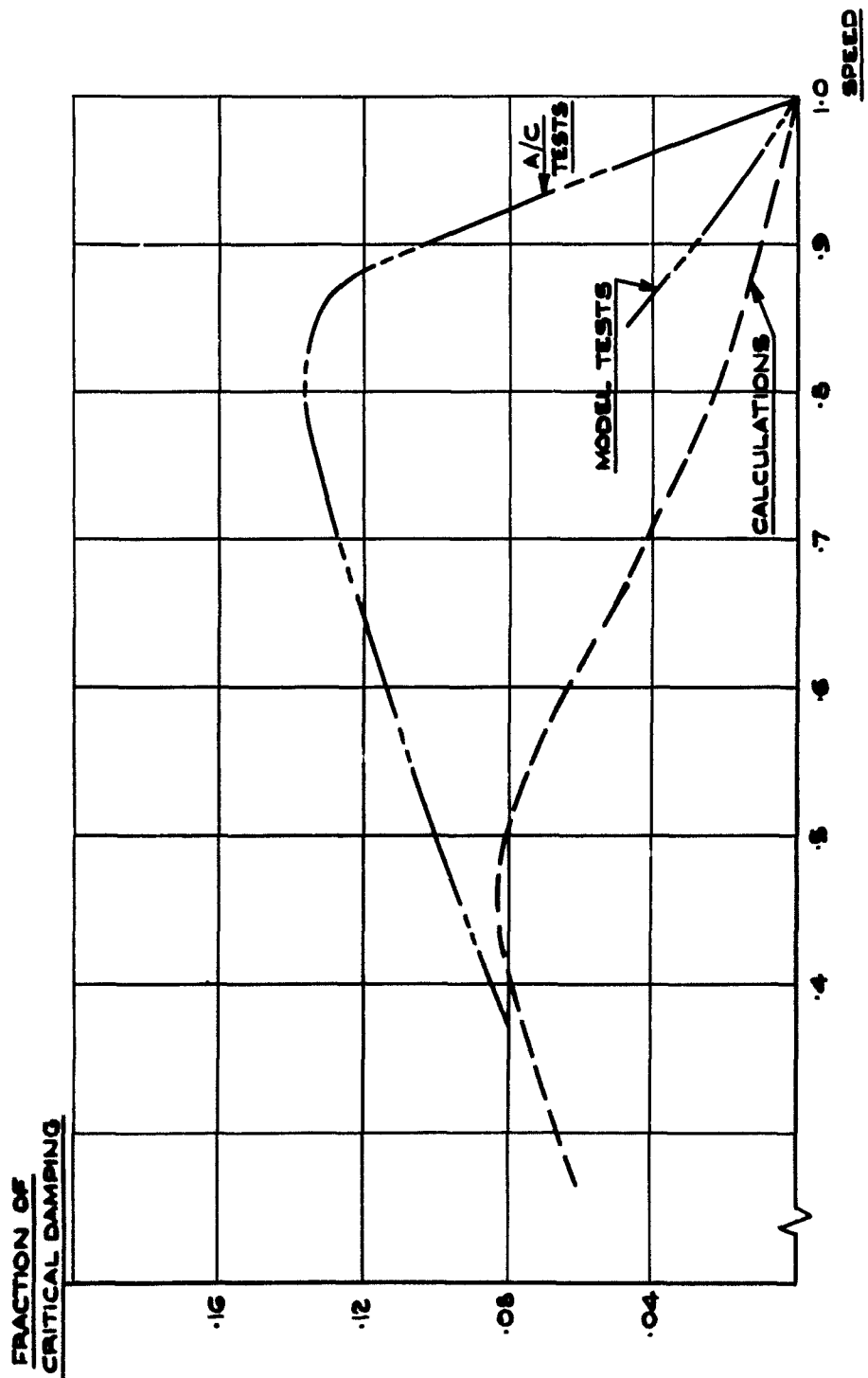


Fig.10 Comparison of model tests, calculations and aircraft tests. Approach to fin flutter